Is the Higgs a Composite Scalar?

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The Higgs Boson

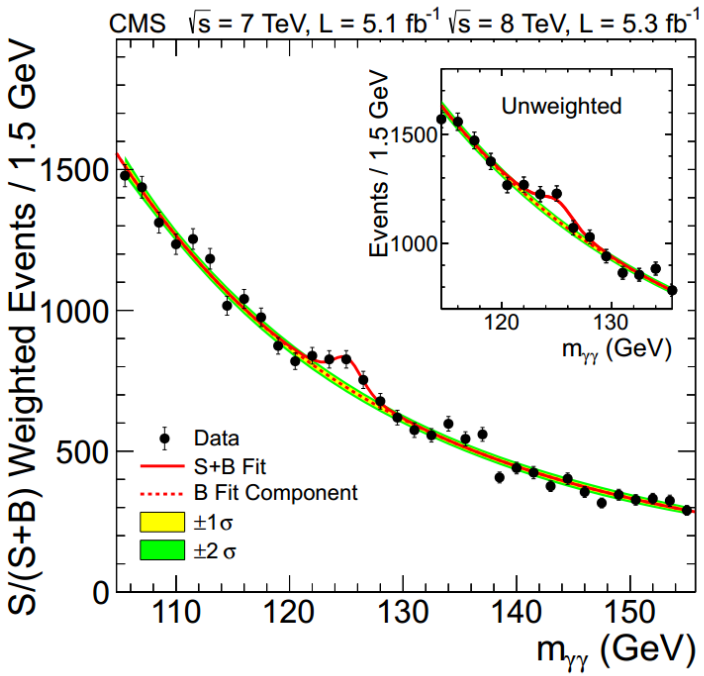

Figure : [Phys. Lett. B 716 (2012)]

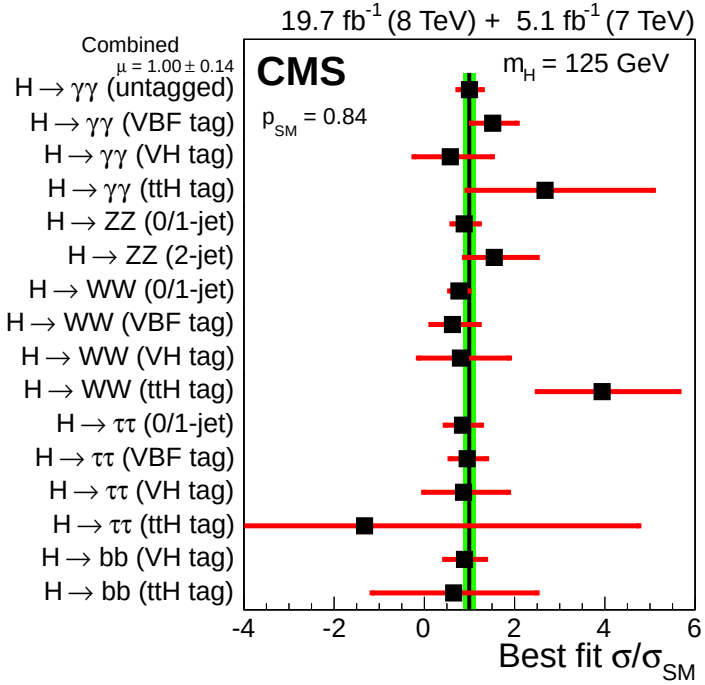

Figure : [Eur.Phys.J. C75 (2015)]

- The Higgs Boson looks very Standard Model.
- There's still the need for a UV completion.

A Composite UV Completion

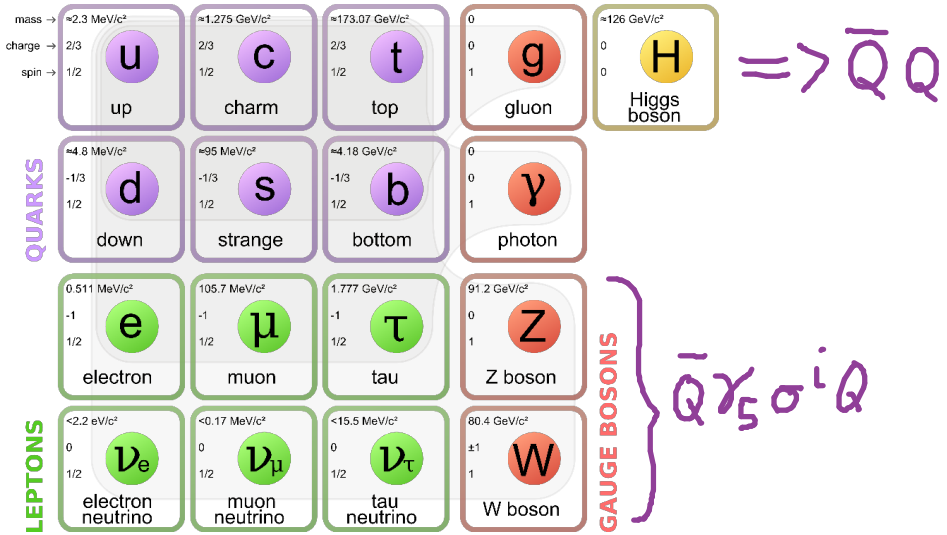

Figure : Modified from Wikipedia: "Standard Model"

- Higgs: $\bar{Q}Q$ scalar composite of strong dynamics.

Not QCD!

The new sector can't just be scaled up QCD.

- QCD has...
  - a broad scalar close to the vector mass,
  - a large S-parameter, and
  - no walking regime.
- More flavors can produce different, interesting behavior.

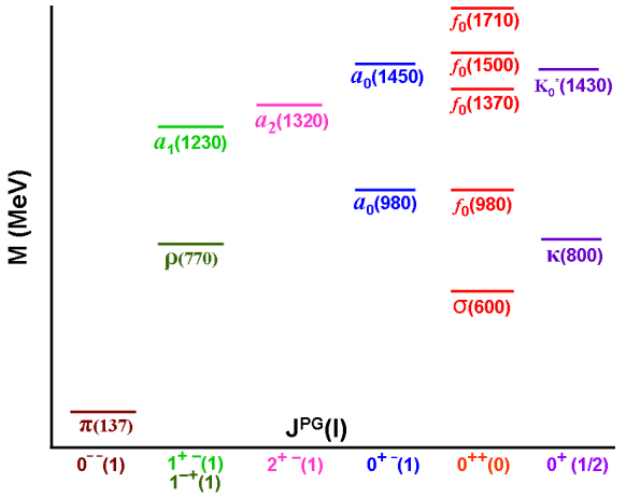

Figure : [Phys.Rev. D76 (2007)]

Composite Models

- It is not easy to build a viable composite model for EWSB.
- Broadly speaking, there are two steps:

1. Pick a general model and study if it has certain features.
2. Worry about connecting it to the Standard Model.

Composite Models

- It is not easy to build a viable composite model for EWSB.
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1. Pick a general model and study if it has certain features. $\leftarrow$ This talk
2. Worry about connecting it to the Standard Model.

Multi-flavor QCD

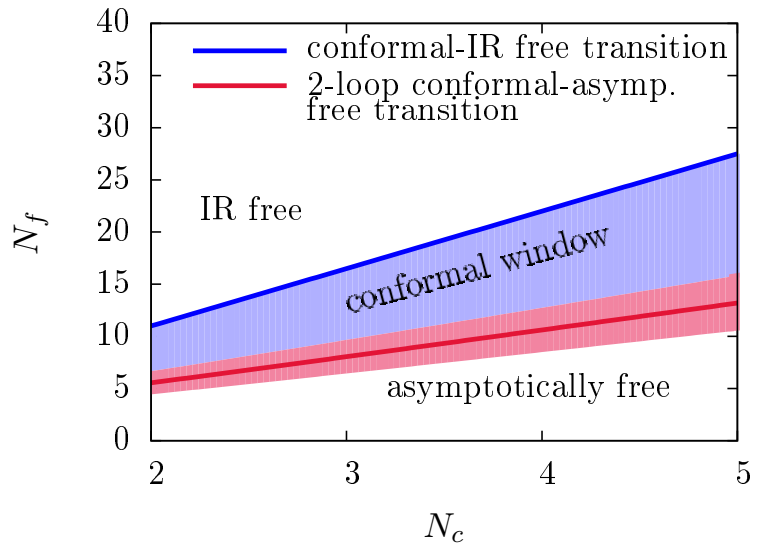
- The interest in multi-flavor QCD is motivated by the beta function.

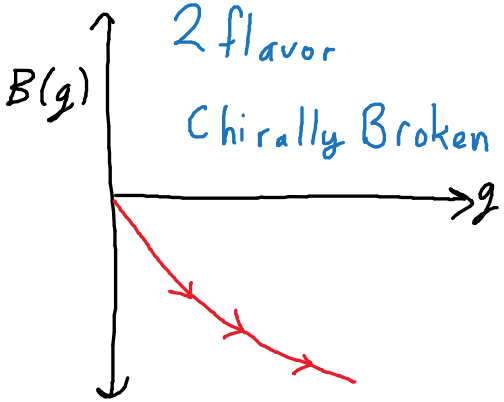
$$\beta(g) = -\beta_0 g^3 - \beta_1 g^5 + \mathcal{O}(g^7)$$

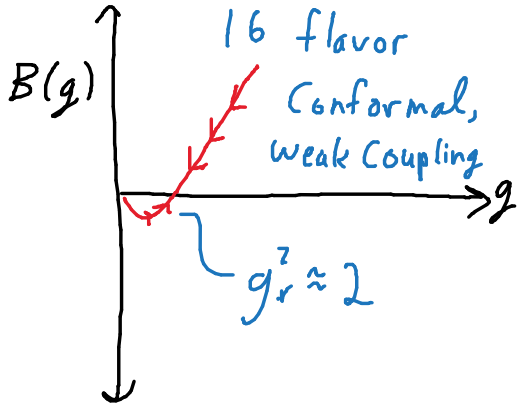
$$\beta_0 = \left[\frac{11}{3}N_c - \frac{2}{3}N_f\right]/(4\pi)^2$$

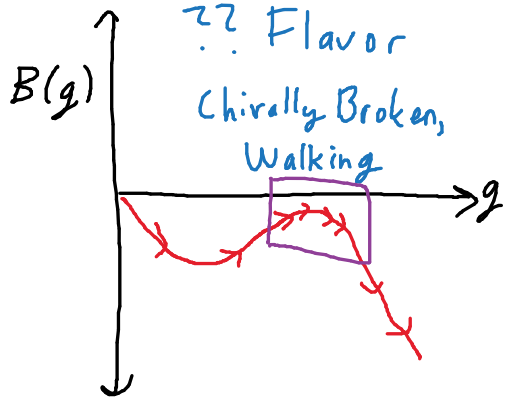
$$\beta_1 = \left[\frac{34}{3}N_c^2 - \left(\frac{13}{3}N_c - \frac{1}{N_c}\right)N_f\right]/(4\pi)^4$$

$\beta_1 = 0 \rightarrow N_f \approx 8.05$





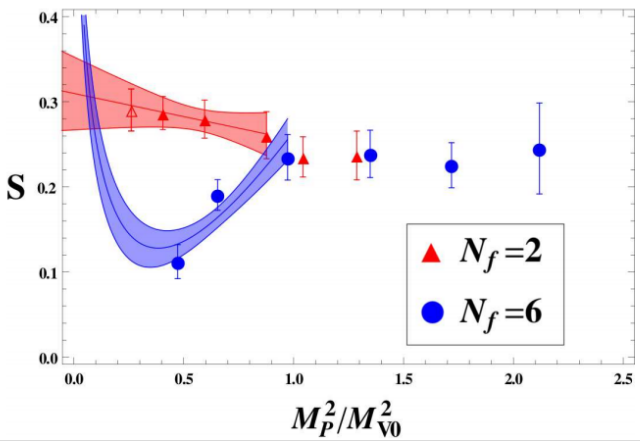




The lattice and many-fermion physics

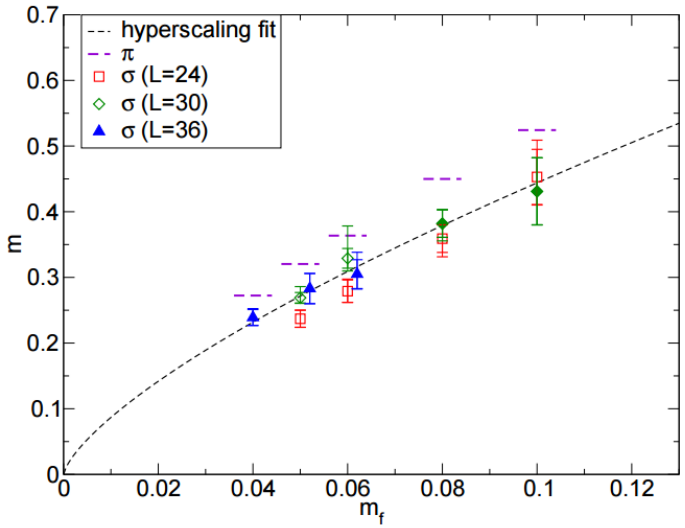
- We can use the lattice as a probe of non-perturbative physics.

- The lattice has indicated S parameter suppression with more flavors.



[Schaich, LATTICE 2011, arXiv:1111.4993]

- It has also indicated that $SU(3)$ 12 flavor is conformal.



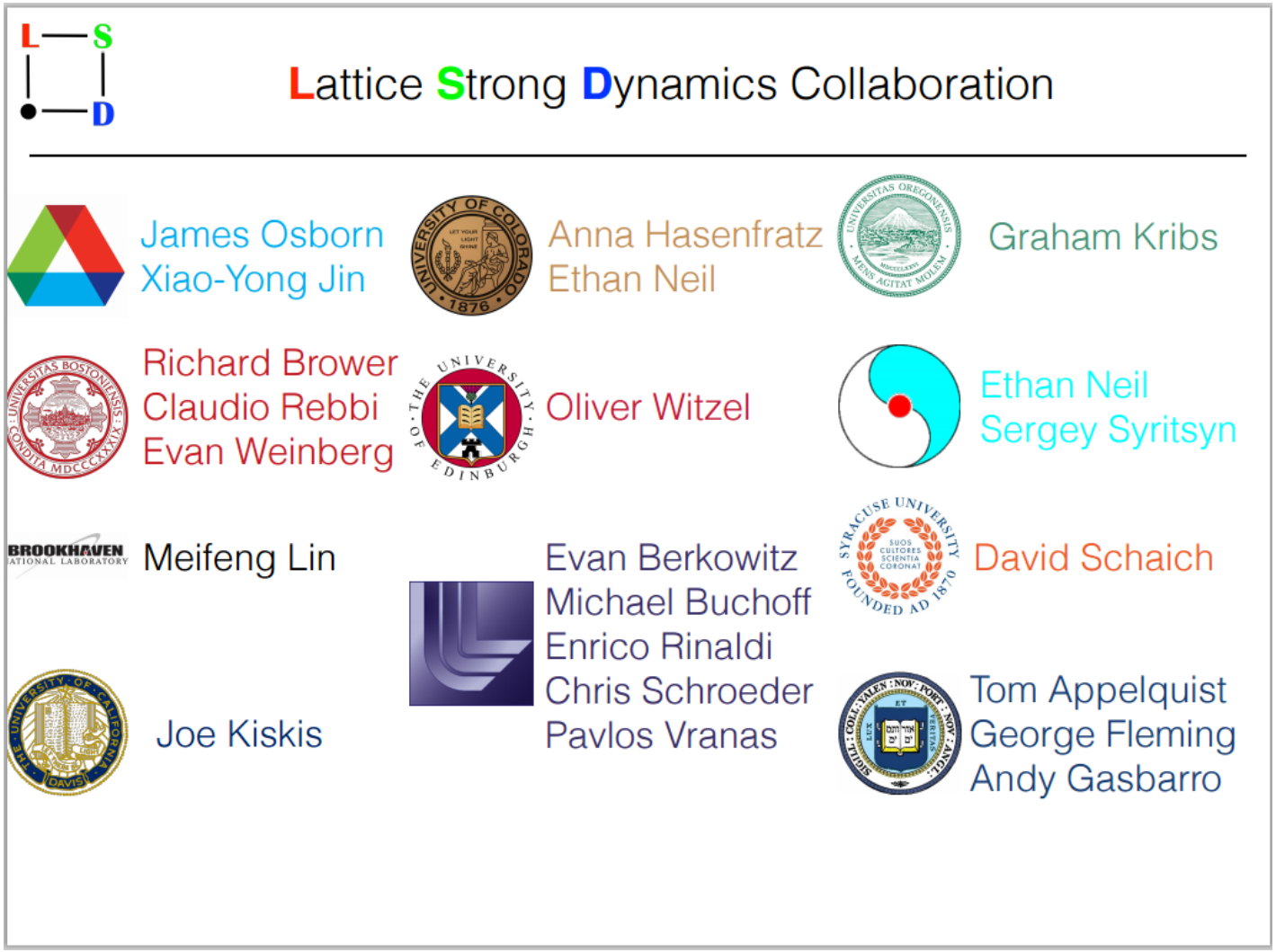
[Aoki et al., LATTICE 2014, arXiv:1501.06660]

- And, in the mass-deformed theory, has a light scalar.

Our model

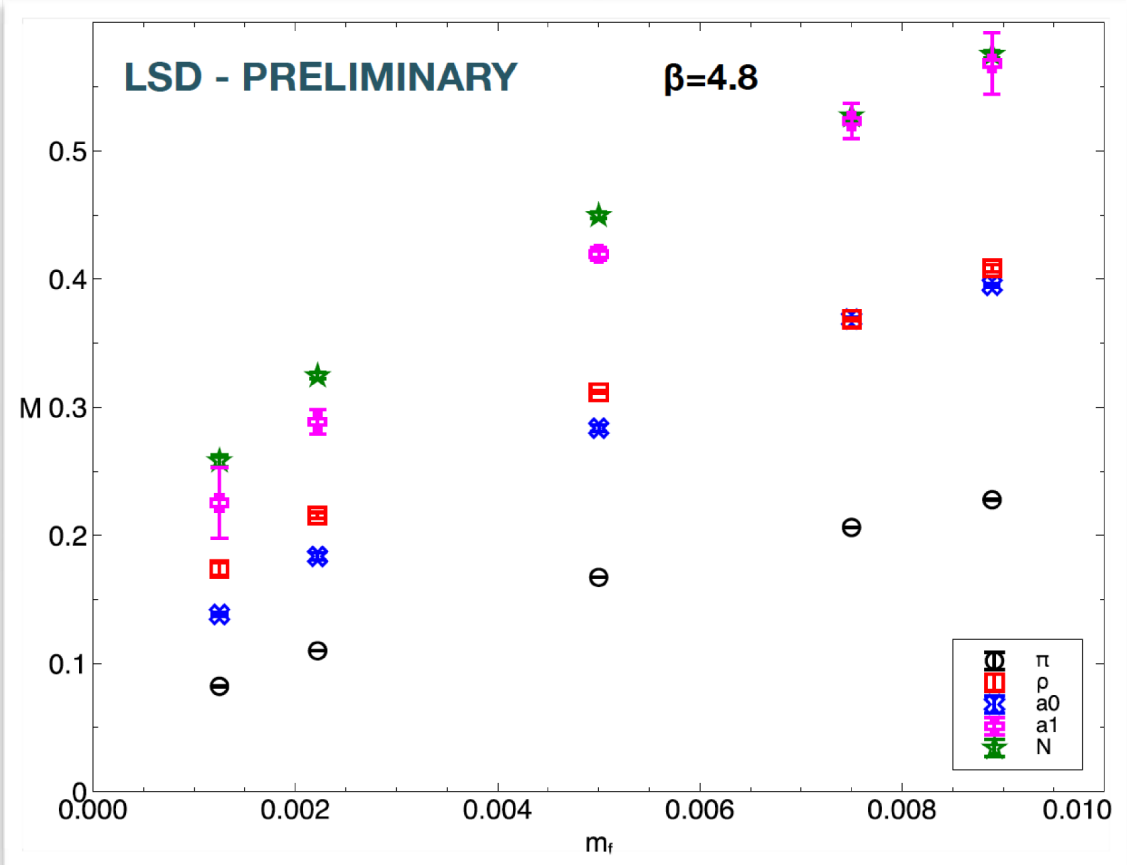
1. Pick a general model and study if it has certain features.
   - Lattice study of $SU(3)$ with 8 fundamental flavors
     - Chiral Kogut-Susskind "Staggered" fermions: multiples of 4 flavors.
   - Right near 2-loop (strongly coupled...) opening of conformal window.
   - Likely confining, but possibly conformal. We cannot definitively tell.
     - "Feature, not a bug."
2. Worry about connecting it to the Standard Model.

LSD Collaboration



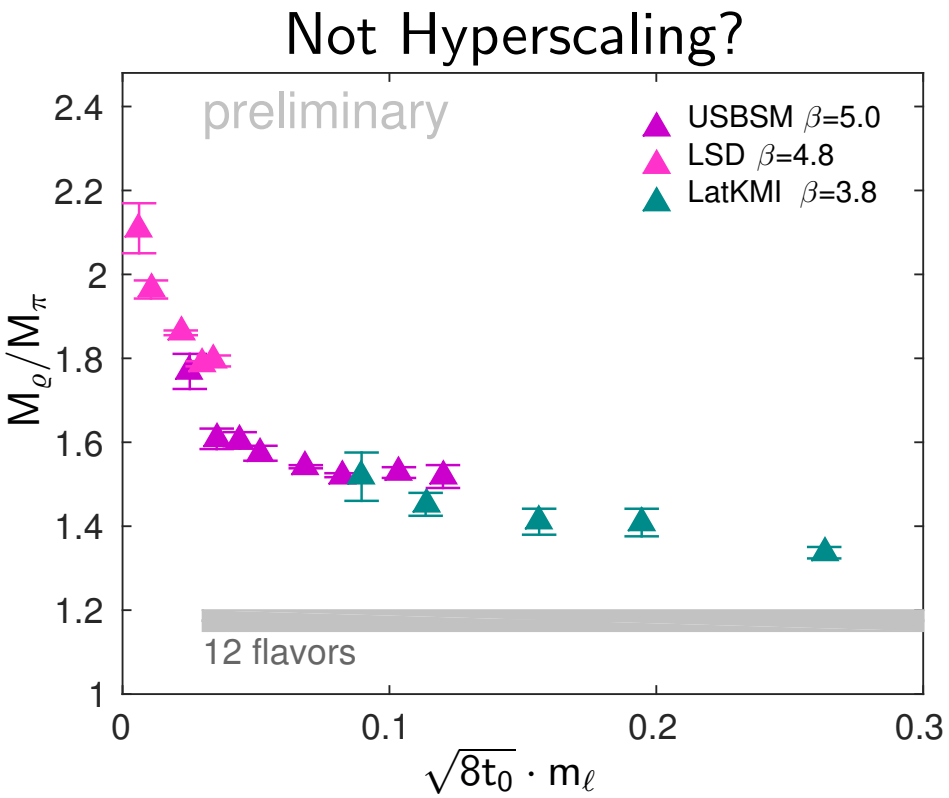
Special thanks to George Fleming, Anna Hasenfratz, Enrico Rinaldi, and Oliver Witzel for plots and useful discussions!

Non-singlet spectrum



- Spectrum depends heavily on the fermion mass.
- Unlike QCD: shouldn't trust ChiPT here.

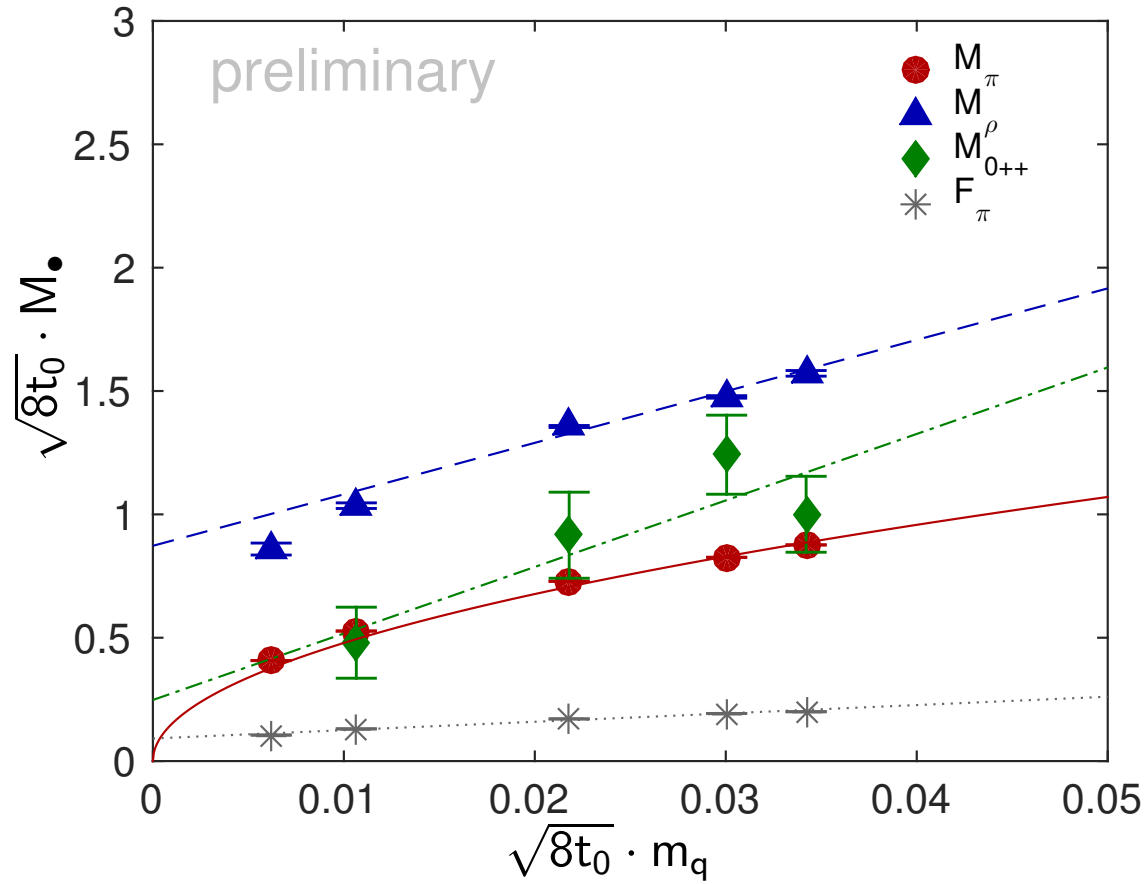
Non-singlet spectrum



- Looks chirally broken, or maybe conformal with scaling corrections.
  - Has interesting dynamics: $M_\rho > 2M_\pi$
- LatKMI data [Y. Aoki et al. 2014], USBSM data [Schaich, PoS Lattice2013 072]
- Boulder 12 result [Cheng et al. 2014]

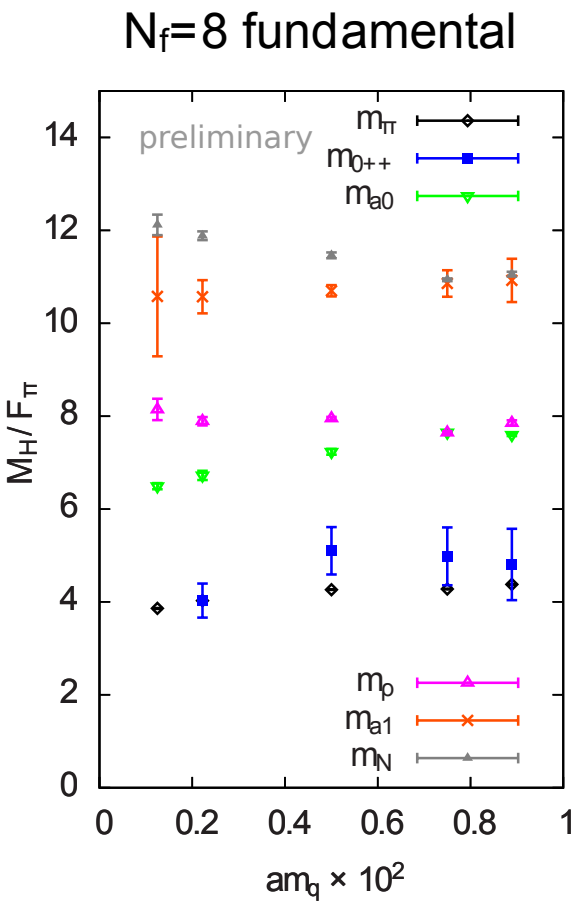
Singlet spectrum

- Measure the 0^{++} with a meson operator. [Ohki talk Wednesday]



- The 0^{++} tracks the Goldstone boson in this regime.
- Very different from QCD!

Overview



- Look at ratios with $F_\pi \approx v \approx 250 GeV$
- Light $0^{++} \approx \pi < \rho, 2\pi$
- $M_\rho / F_\pi \approx 8$: 2TeV di-boson resonance?
  - Ratio seen in QCD
  - Also seen in $SU(3)$ 2 flavor sextet [LatHC 2015 (LATTICE2015)]
  - Perhaps a general feature?
- $M_{0^{++}} / F_\pi \approx 3 - 4$: What would a top loop do?
- Rich spectrum of other states.

8 flavors going forward

1. Pick a general model and study if it has certain features.
   - 8 flavors is a great model to learn about light scalar dynamics.
   - What is the low energy theory when there's a light scalar?
     - We're on the UV complete lattice.
     - We can compute pi-pi scattering, pi-sigma scattering, sigma-sigma scattering.
     - From a field theory standpoint, we can learn a lot.
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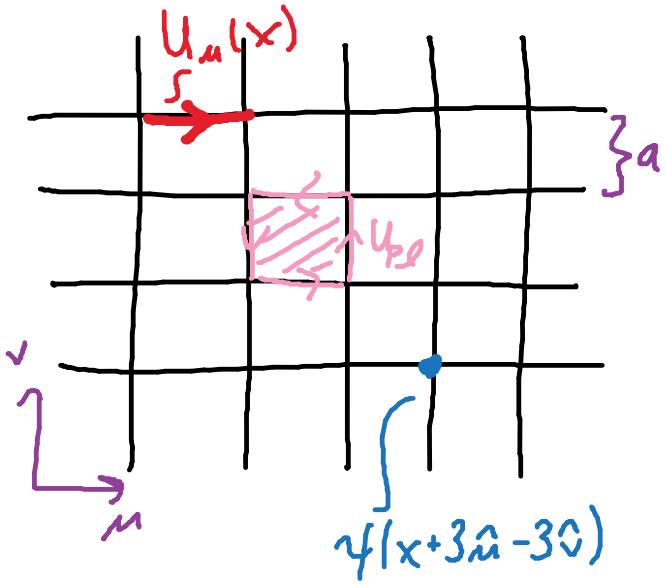
Thank you!

Backup

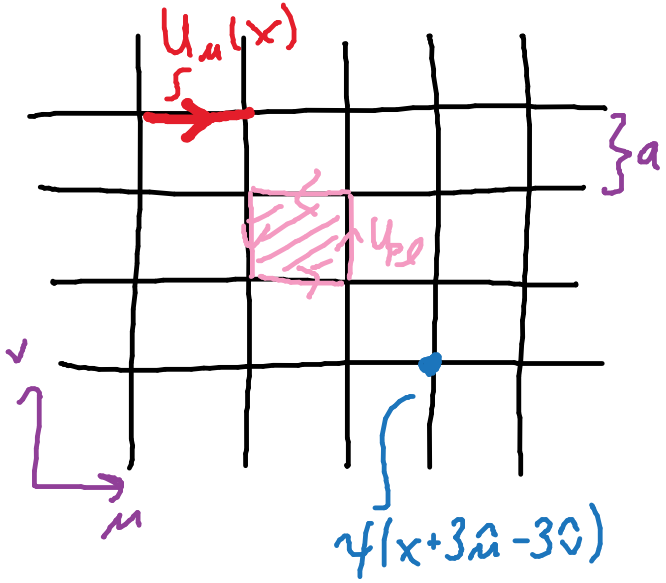
Backup: The Lattice



- Studies are done on 4-dimensional $L \times L \times L \times (2L)$ lattices.
- Common values are $L = 24, 32 \rightarrow \mathcal{O}(1 \text{ million})$ sites.

$$\mathcal{Z} = \int [dU d\bar{\psi} d\psi] e^{-\frac{1}{g^2}F^2 - \bar{\psi}_i \not{D} \psi_i - m_\ell \bar{\psi}_\ell \psi_\ell - m_h \bar{\psi}_h \psi_h}$$

Backup: The Lattice



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$$\mathcal{Z} = \int [dU] \, \det(D^\dagger D + m_h^2)^{N_h/2} \, \det(D^\dagger D + m_\ell^2)^{N_\ell/2} \, e^{-\frac{1}{g^2} F^2}$$

- Having multiple flavors is just adding more fermion determinants.

Backup: 8 flavors finite temperature studies

- We base our 8 flavor runs on existing results.

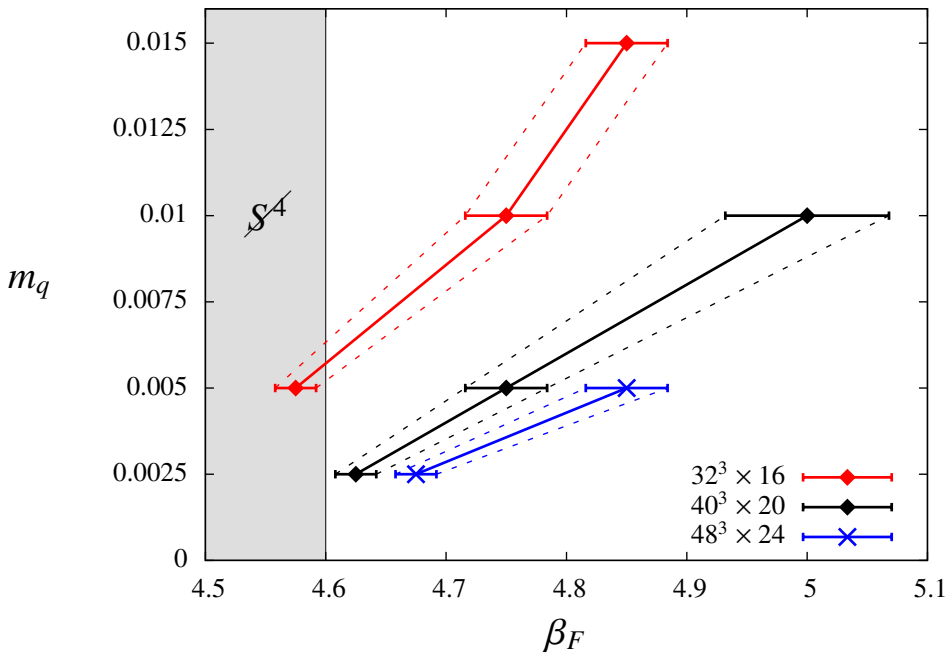

Figure : Finite T studies by Boulder / LSD, in preparation

- Run at strong couplings safe from deconfinement and lattice phases.

Backup: Lattice simulation details

- Lattice study of $SU(3)$ with 8 fundamental flavors
  - Gauge action: fundamental-adjoint with $\beta_a = -\beta/4$ [Cheng et al. 2013][Cheng et al. 2014]
  - Fermion action: nHYP smeared staggered [Hasenfratz et al. 2007]
  - Software: HMC and most measurements in FUEL [J. Osborn]

Backup: Scalars in QCD

- There are five (maybe 6) isosinglet scalars below the charm threshold.
- $f_0(500), f_0(980), f_0(1370), f_0(1500), f_0(1710)$ (and maybe $f_0(1790)$).
- Quark model: only two can be predominantly $\bar{Q}Q$.
- Others: meson molecule, diquark pair, glueballs?

Backup: Strategy for disconnected diagrams

- 8 flavors uses the following setup!
  - 6 $U(1)$ sources with dilution in time, color, and even/odd spatially
  - Improved estimator for $\langle \bar{\psi}\psi \rangle$
  - Dilution in time, color, even/odd space
  - Improved estimator for disconnected piece
  - Still need large statistics to suppress gauge noise
- Analysis strategy.
  - Correlated fit to both parity states
  - Vacuum subtraction introduces large uncertainties
  - Fit an additional constant
  - Equivalent to fitting the finite difference $C(t+1) - C(t)$

$$C(t) = c_{0^{++}} \cosh\left(M_{0^{++}}\left(T/2 - t\right)\right) + c_{\tilde{\pi}_{sc}}\left(-1\right)^t \cosh\left(M_{\tilde{\pi}_{sc}}\left(T/2 - t\right)\right) + v$$